GALILEO SPACECRAFT OPERATIONS

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1. Introduction

On December 7, 1995, the Galileo spacecraft arrived at Jupiter to begin intensive scientific observations of Jupiter, its satellites, and its magnetosphere. Because of loss of use of the high-gain antenna, most of the scientific data collected during each of the satellite closest approaches is recorded on the tape recorder for later playback to Earth. Science data are recorded at several rates from 7.68Kbps to 806.4Kbps and later returned to Earth at downlink telemetry rates ranging from 8 to 160bps. The encounter data from eleven science instruments are stored on a single tape recorder with a usable capacity of about 750 million bits. Also, radio science data rue collected using the downlink radio frequency signal generated by an ultra-stable oscillator in the spacecraft radio frequency subsystem (RFS). Four of the eleven science instruments are mounted on a 2-degree-of-freedom scan platform located on the spacecraft despun section. These instruments perform remote sensing optical scientific observations during every satellite encounter. The remaining seven science instruments are located on the spacecraft spun section. All (except the EUV) are fields and particles science instruments. Most are mounted on the science boom that extends outward from the spacecraft main bus. These instruments collect science data during both the satellite encounter and the Jupiter-Orbit cruise phases.

The Galileo orbital tour provides a unique opportunity for making many intensive and diverse scientific observations of the Jovian system. To perform the scientific observations and return the data, it is essential that the Galileo spacecraft remain in “good health” to successfully accomplish all the needed activities at the required times. Health, safety, and other maintenance activities include periodic short firings of the propulsion subsystem’s 1O-N thrusters to prevent clogging of in-line filters, gyro calibrations to meet pointing performance, tape recorder conditioning about every 30 days to reduce the chances of tape sticking, regular Earth attitude pointing updates to maximize downlink telemetry performance, and flight software updates as necessary.

The remainder of this paper describes a typical orbital spacecraft operations profile, summarizes how we get the spacecraft to do what it needs to do, and the process by which science and engineering requirements and requests are translated into commands and finally radiated to the spacecraft.

2. Typical Orbital Operations Profile-Overview

Jupiter and satellite encounters occur at intervals from about 30 to 80 days. Science observations and data return activities are highly integrated and optimized for each encounter. During a typical spacecraft orbit, three background sequences are used—one encounter and two cruise sequences The encounter sequence covers the time period about ±3 days around satellite closest approach. During the spacecraft orbital Cruise period, nominally three propulsive maneuvers are performed A pre-encounter maneuver is performed at about 3 days inbound to closest approach to fine tune the satellite flyby to the aim point.. A post-encounter maneuver is performed about 3 days after satellite closest approach to correct for flyby trajectory dispersions caused by errors at the flyby. The third maneuver is performed at apoapsis to correct the then predicted errors at the next satellite encounter aim point.

The majority of the orbital tour time between satellite encounters is spent returning tape recorder data recorded during the previous encounter. In addition to returning recorded data, red-time fields and particles science data are returned, and all the needed engineering activities are performed. A typical satellite orbit profile is shown in Figure 1.

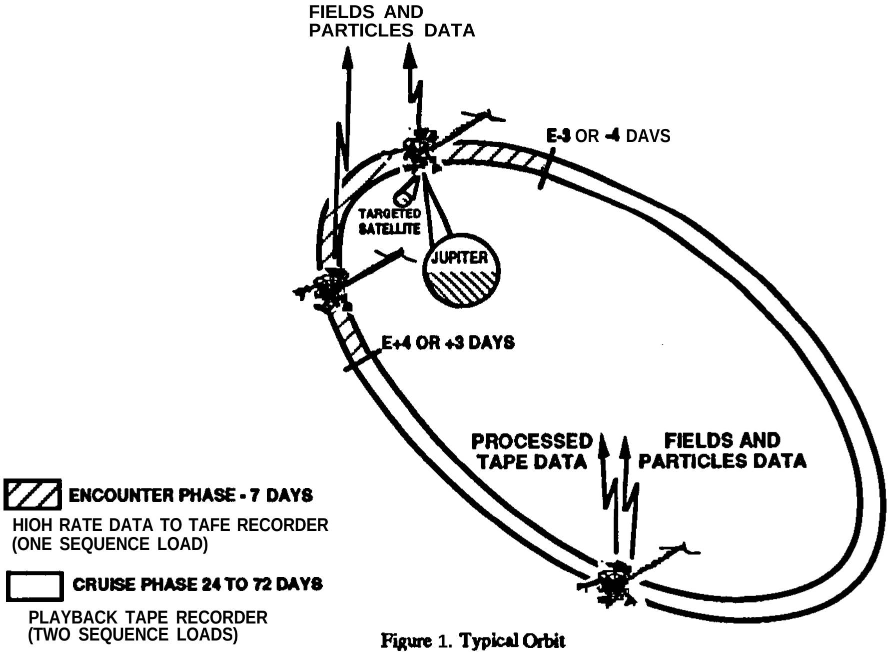


Figure 1. Typical Orbit

3. Sequence Description Overview-Telling the Spacecraft To Do What We Need It To Do

The Galileo spacecraft is controlled by redundant central computers with six microprocessors and 384 Kbytes of RAM. For all planned spacecraft activities the central computer memory must be loaded from the ground with all the necessary commands needed to perform those activities. Every activity must be defined months in advance to permit science and engineering activities to be integrated together, broken down to the individual command level and put in proper time order for execution. The integrated proper time order of commands is called a sequence. Sequence-s are the primary means for controlling spacecraft activities including the operating mode and state of all the engineering subsystems and science instruments. Sequences may be small-issuing several hundred commands, (e.g., maneuvers or anomaly investigations) or sequences may be large—issuing more than four thousand commands, as for satellite encounters.

Two types of sequences are used—specifically, background sequences and reserve box sequences (RBS). Background sequences are larger and typically control spacecraft activities for a predetermined time, e.g., satellite encounters and orbital cruise. The RBS is the smaller sequence and controls a special activity (e.g., maneuver) to be performed within a time window allocated within the background sequence. For every satellite encounter, the sequence contains all the commands needed to control tape recorder speed and direction, optical-science platform pointing and slewing, data collection mode and data rate, science instrument operating modes and configuration control, power margin management, and other required functions. The three background sequences combined with the three maneuver RBSS typically issue about 6000-7000 commands every orbit.

4. Sequence Development Process—Encounter and Cruise Sequences

4.1 GENERAL

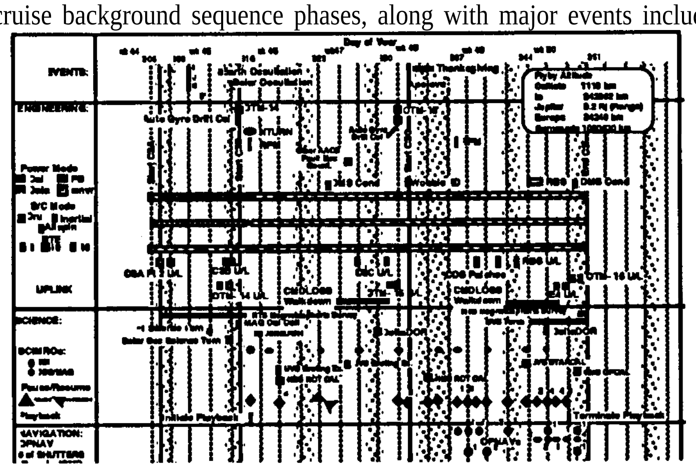
The following paragraphs briefly describe the sequence development process from request inputs to sequence transmission to the spacecraft. The sequence development process is a highly automated, intensive process using many computer programs and tools and skilled personnel. It takes many dedicated people in several multidisciplinary teams working diligently with a common goal to develop the encounter and cruise orbital tour sequences

4.2 ENCOUNTER

Of the three background sequences used during each orbit, the most intensive and ambitious is the encounter sequence. Because each encounter has its own unique set of optimized observations, the encounter sequence contains numerous highly integrated complex engineering and science activities. Particularly challenging is how best to use the tape recorder to collect the most important science data. ‘he tape recorder usable capacity of about 750 million bits must be negotiated among the science teams, and allocated to each of the instruments so that every science instrument gets a reasonable share of this precious resource for making its observations. Furthermore, because of the Command and Data Subsystem (CDS) memory usage strategy, the maximum amount of memory an encounter sequence may use is about 39,000 bytes (typical command size is 8 bytes). Because of these considerations, developing an encounter sequence is a challenging task. Early in the development process, requests for science instrument observations are identified and prioritized within the science teams to form an integrated overall encounter science observation plan. Correspondingly, the engineering requests (maneuvers, calibrations, etc.) go through a similar process within the navigation, sequence, and spacecraft engineering teams. After the science and engineering requests are integrated, the requests are merged by the sequence team into a preliminary sequence of events that should meet the science and engineering needs, Within each team, during the identification and prioritization process, there are many "puts and takes." When science observation conflicts or incompatibilities arise, the science teams work vigorously and objectively to reach an agreed-to science observation profile. Most of the time agreements are reached at the team level but, occasionally, resolution requires negotiation with the science instrument principal investigators and the project scientist. A similar process is used to resolve engineering-related conflicts and incompatibilities. Resolution, of course, involves negotiation among the appropriate office managers and other project personnel.

As the sequence development process continues, sometimes new conflicts or incompatibilities arise when the sequence team merges the science and engineering request files with updated downlink telemetry performance estimates. This merging of science and engineering request files with updated telemetry performance sometimes results in science and engineering activities being changed. 'he sequence team identifies and submits every conflict to the appropriate team and personnel for assessment. Nearly all the time, the conflicts are solved at the working team level. In many cases, resolution is as simple as slightly moving a science observation or moving an engineering activity by several hours or a &y, or even accepting the conflict, if the consequences are acceptable. However, there are instances when a science instrument observation plan maybe significantly modified in order to deliver a safe, operable, reliable overall encounter sequence on schedule. Fortunately, significant changes late in the process are not common. Though rare, when needed, the approval of the principal investigator and project scientist are obtained. After all conflicts are resolved, the sequence team produces a final sequence of events file that lists all the named commands needed to perform the activities. This final command listing file is subsequently translated into computer language "1"s and "0"s to be loaded into the spacecraft memory.

Figure 2 illustrates the actual sequence of events timeline (daily resolution) for the Callisto 3 (C3) orbital sequence profile. Specifically identified are the encounter and hvo cruise background sequence phases, along with major events including time



windows for propulsive maneuvers and engineering activities. Figure 3 illustrates a more detailed (hourly resolution) encounter time period with significant science observations and engineering events. Similar figures are developed for every orbit and pro e an excellent source of summary information.

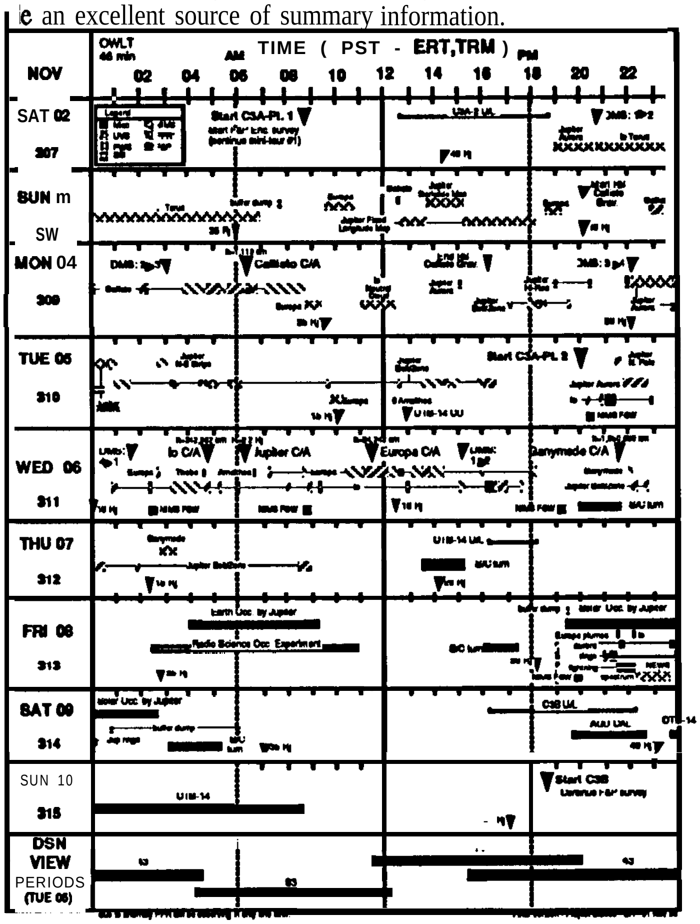


Figure 3. Summary of spacecraft operations for Callisto encounter (

5. Orbital Cruise Sequence

5.1 GENERAL

orbital cruise sequences are developed using the same process as for encounter sequences. The major activities in the cruise sequences= (a) return tape-recorded science data stored during encounter, (b) return real-time fields and particles science data, (c) establish time periods to uplink and execute the propulsive maneuvers, (d) perform engineering and science calibrations, (e) perform spacecraft health and safety activities, and (f) collect navigation data. To accomplish most non-playback activities (e.g., health and safety activities) during the orbital cruise period, the tape playback process is paused and resumed before and after the planned activity. This pause and resume playback capability permits activities to be perfumed with minimal impact to science data return.

5.2 PROPULSIVE MANEUVERS

To accurately navigate the Jupiter orbital tour, it is essential that the spacecraft nominally perform three propulsive maneuvers every orbit. The particular requirements for each maneuver are derived from navigation information acquired from the spacecraft radio frequency signal (Doppler tracking data). Additionally, optical navigation information is acquired by taking images in every orbit of a star field background containing the satellite of interest and sometimes other satellites. The image data along with the Doppler tracking data provide the necessary sources of information to compute the magnitude and direction of required maneuvers. Based on the navigation information, the required delta velocity is broken down into "segments" that can be achieved by appropriately firing the propulsion subsystem thrusters. All remaining propulsive maneuvers are performed using the 1O-N thrusters. The thrusters must be operated in pulsed mode to ensure thruster thermal safety. Except for thruster health maintenance, the thrusters are operated with the spacecraft spinning near 3 rpm in the dual-spin mode. A spacecraft delta velocity may be imparted using a "vector mode" method or a "turn and burn" method. For vector mode, the spacecraft pointing direction is unchanged and the delta velocity is achieved by appropriately combining axial and lateral delta velocity vector components from the P, L, or Z thrusters (see Figure 4). For larger delta velocities, the spacecraft is turned to the burn attitude to accomplish the delta velocity in a particular direction (see Figure 5).

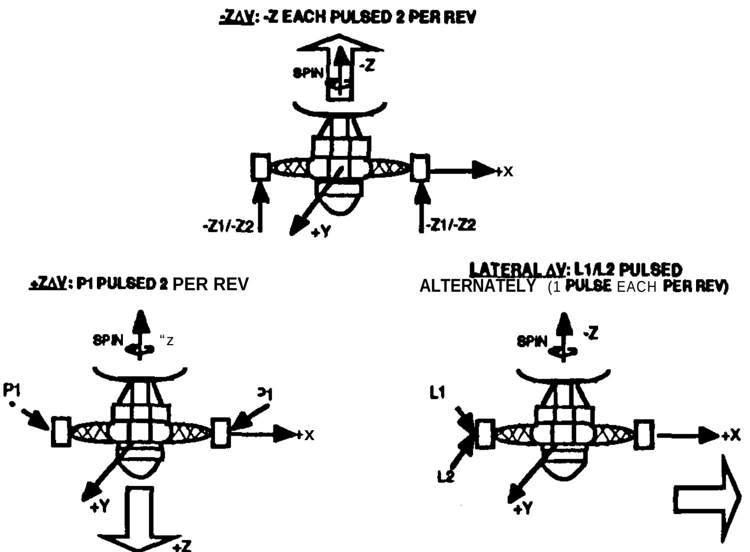


Figure 4. Delta Velocity Maneuvers

The 1O-N delta velocity activities are all performed in an open-loop manner. Thruster performance is predicted based on predicted tank pressures expected to exist at the time of the maneuver thruster firings. Additionally, thruster on and off times snd the number of pulses needed to achieve the delta velocity are calculated based on predicted thruster performance. The predictions must account for thermally induced pressure changes resulting from unavoidable system power margin variations which occur during encounter and cruise operations when the spacecraft electrical load may fluctuate several tens of watts for a few minutes or several watts for a few days.

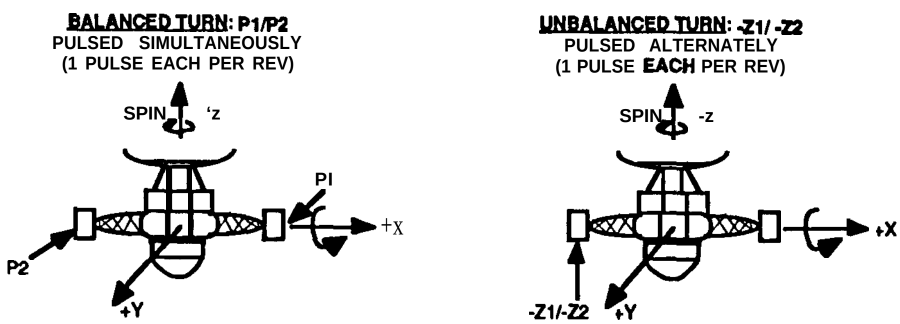


Figure 5. Turn Maneuvers

Maneuver sequences are sent to the spacecraft in an RBS generally oneday prior to the planned maneuver execution start time. Nearly all maneuvers can be performed within an 8-hour time period. In eight hours, a delta velocity between 7 and 12 m/sec can be achieved depending on the thrusters used. Figure 6 illustrates the actual maneuver activity timeline used for the vector mode Orbit Trim Maneuver (OTM) performed near G2 apoapsis on October 8,1996. This maneuver imparted a delta velocity of about 0.59 m/sec by firing 288 P-thruster pulses and 20 L-thruster pulses.

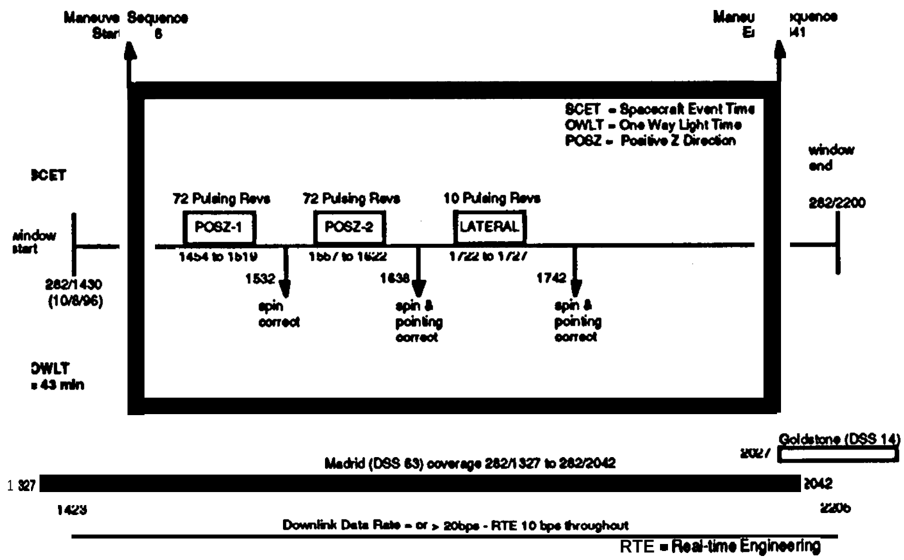


Figure 6. Typical Maneuver Description

5.3 Data Return Strategy —Monitoring and Control

As mentioned in preceding paragraphs, most of the encounter science data are stored on the four-track tape recorder. The onboard playback process is autonomously controlled by flight software using uplinked playback tables defining the data to be returned.

During the development of the science encounter observation sequence, the science data return baseline plan is developed. Generally, all tape receded data cannot be returned during the cruise playback period. Thus, it is necessary for the ground controllers to continuously monitor the progress of playback, compare it with baseline plan expectations, and modify playback tables by ground command, as appropriate, to assure that the most important science observation data are returned. The data return baseline plan identifies the encounter observations to be returned during the entire allocated cruise playback period. The baseline playback plan accommodates sharing of the downlink channel bit rate capability with real-time fields and particles science data. Data return estimates are made on the basis of data compression ratios derived from expectations of the observed scene characteristics, e.g., contrast level for an image scene. After the playback activity begins, the actual playback may be altered by the flight **team** by transmitting new playback instructions via a playback table update. If the playback performance process is significantly different from the plan, data compression **ratios** may be **modified** by ground command. Furthermore, to ensure return of the most important science **data,** some recorded data are skipped over and not returned at all, i.e., deselected from the **downlink.** Significant changes to the baseline plan and subsequent update data return plans are reviewed by the project **scientist, science** principal investigators, and the Project **Office.** Data playback table updates are usually transmitted to the spacecraft about two times per week, although more are possible if needed.

To return data to Earth, the recorded data are read from the tape recorder at 7.68 kbps into Command and Data Subsystem (CDS) buffers in small increments. **The recorded** incoming data are **compressed onboard** the **spacecraft** based on compression **parameters provided** by the science team. For example, the visual image **camera** &tame compressed using a **lossy** integer cosine transform **(ICT)** algorithm. The data compression is performed by the Attitude and Articulation Control Subsystem **(AACS)** on-line microprocessor using its spare off-line memory as data storage areas. Because of AACS processor timing margin limitations, appreciable ICT compression cannot be **performed** when the AACS is in inertial mode, i.e., gyros on and in the control loop. Fortunately, this limitation does not have a major **effect** on the return of science data because most of the time the AACS is in cruise mode without gyro control. Other science data **are** compressed by **the** CDS using 1oss1ws compression algorithms, After data are **compressed,** they are routed through the **CDS downlink** telemetry channel, **coded,** and transmitted to Earth atone of the eight supportable data rates between 8 and **160bps.**

The total amount of data (real-time and stored) that can be returned per orbit varies between 100 million bits and 500 million **bits** depending on communications range and the orbital period, i.e., time to the next encounter. Data **are returned** using a 13-watt, fully suppressed carrier, S-band radio **downlink** signal. The data rates are selected by the commands in **the** cruise sequences to optimize return, taking into account ground receiving station performance **variations** caused by changing antenna elevation angles over each **tracking** pass. The Deep Space Network **(DSN) Canberra,** Australia, site is the primary ground **receiving** tracking site for returning playback data. The length of the Canberra tracking pass is about 12 hours each day, and the receiving antenna elevation angles are higher than at the other two tracking sites at Madrid, Spain, and **Goldstone,** California. The Canberra site normally uses the 70-meter antenna station arrayed with two local 34-meter antenna stations, the 64-meter antenna at **Parkes** located about 180 km away, and the **70-meter** antenna station at Goldstone during the roughly 5-hour **Goldstone—Canberra** overlap view period. The **Canberra** 70-meter station **also uses** a new **ultra** cone receiving system which significantly reduces the system noise temperature and enables **enhanced downlink** telemetry performance. Because science data return is so important, needed ground commanding is **normally** scheduled over the **Madrid,** Spain, **or Goldstone,** California, 70-meter station passes to minimize the loss of the data return that would result from switching to an alternate cone to permit commanding from Canberra.

In the ideal data return scenario, all data that are transmitted from the spacecraft are received and processed by the ground system and there would be no data dropouts. Unfortunately, data dropouts do occur because of operational procedure problems, software anomalies, random hardware failures, or weather effects. To date the amount of data not captured due to dropouts has been relatively small, generally less than 5% on average for the Ganymede 1, Ganymede 2, and Callisto 3 encounter data return activities.

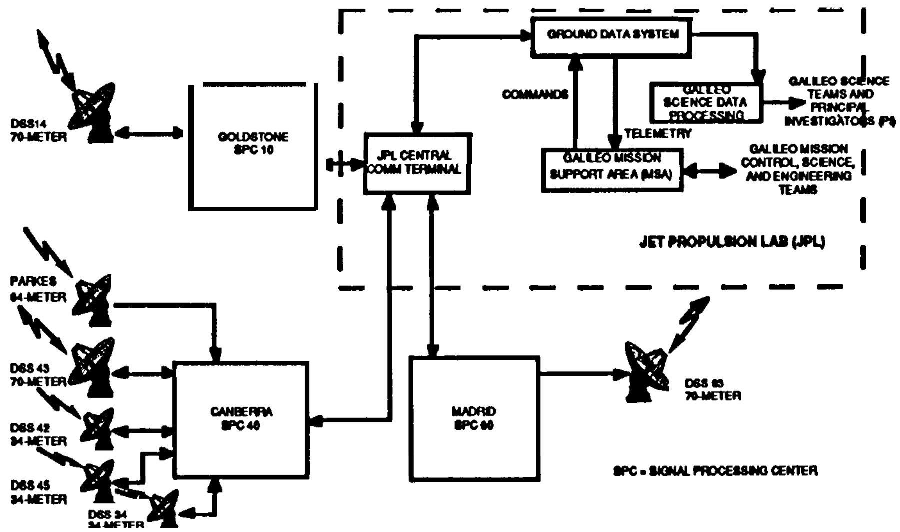


Figure 7. Ground Communication Overall End-To-End Data Flow

6. Sequence Approval and Transmission

The Mission Director (MD) must authorize the transmission of all sequences sent to the spacecraft. The MD's authorization to transmit a sequence is usually given one or two days before the sequence is scheduled to go active onboard the spacecraft. Authorization is formally given at a sequence approval and command conference meeting attended by the appropriate science and engineering team members, the sequence integrators, the personnel responsible for implementing the uplink transmission, and the appropriate Project Office personnel. This is the meeting where final testament is given that the as-built sequence meets the negotiated requests and needs, has a high confidence of successful execution (reliable), all disputed items have been resolved or dispositioned, and the sequence is ready for transmission from the DSN within the specified uplink time window. Sequences are normally transmitted to the spacecraft using the 70-meter antenna and the 100KW, S-Band, radio frequency transmitter at Goldstone, California, or Madrid, Spain. The total radiation time to uplink a single sequence command package is about two to three hours. Depending on the size of the sequence, multiple command packages are required to be uplinked to the spacecraft. Figure 7 illustrates the command and telemetry process data flow between the DSN and the Jet Propulsion Laboratory.

7. Conclusion

As of the end of December 1996, the Galileo spacecraft has completed four close encounters with three of the Galilean satellites, has completed 13 OTMS, and has made many significant scientific discoveries. Extremely high resolution images have been returned from the satellites. Indeed, all eleven orbiter instruments have provided a wealth of data about Jupiter, its magnetosphere, and its satellites. Future observations from the remaining satellite encounters are expected to provide greater insight into understanding of the Jovian system. Operating the Galileo spacecraft is a unique, challenging, and highly rewarding experience. Galileo has and will continue to return a rich harvest of science data from the Jovian system.

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